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***Abstract*—The digitalisation of industry and the Industry 4.0 concept with its connected ICTs are important developments for the industry to acquire and implement to be able to keep ahead in competition. In connection to Industry 4.0, the predictive maintenance systems and approach are getting more popular in maintenance. This is because these systems enable a change in the maintenance mind-set where the break-fix mentality is substituted by a predictive maintenance system, such as Condition Based Maintenance (CBM), where the equipment is monitored with the support of ICTs to detect failures before they occur. The Industry 4.0 seems more attainable even for small and medium sized companies because of the drop in the prices of the components of these systems, both in the sensing elements and in the data processing part. The manufacturing methods used in the Integrated Circuit (IC) industry create the possibility to reduce significantly the price tag of sensors and processors. Therefore, the authors go through the CBM approach and technologies, such as Microelectromechanical System (MEMS) sensors as well as such emerging ICTs as the Cloud and Big data. These could offer a turning point in traditional maintenance by widening the amount of monitored assets, allowing multiple parameters to be measured and analysed and enabling wireless and immediate data access across the globe.**

Keywords-CBM; Microelectromechanical System (MEMS) sensors; Internet of Things (IoT); cloud computing; big data analytics

I. INTRODUCTION

In automated manufacturing or process plants, CBM is preferred, wherever; it is technically feasible and financially viable. It involves the acquisition of data, processing, analysis, interpretation and extracting useful information. The automation for machining operations and machine tools have been emphasized upon both in academia and industry for several decades. Successful implementation of automation of manufacturing process requires effectiveness of process monitoring and control systems [1]. However, there are difficulties in the application of CBM such as; the data gathered is generally very large, as the data may need to be gathered from the assets dispersed over a large geographical area. The data may be required to be integrated to provide any useful information. With time, the need may be felt for data acquisition from additional sources and its integration with the rest for interpretation that is more meaningful and finally availability of the expert for converting data into useful information for maintenance. These difficulties identified within the industry have often been solved using a range of ICTs, such as expert systems, artificial intelligence and distributed artificial intelligence [2]. Recent ICTs developments have also brought the use of sensors into the area of maintenance. The Microelectromechanical Systems (MEMS) sensors are becoming popular. The way these MEMS are fabricated enable them to be relatively low priced compared to traditional sensors.

Continuously, the emergent concept of Internet of Things (IoT) facilitates data collection from various sensors, which increases the possibilities of sensor and data monitoring as well as analytics for decision-making purposes. IoT is destined to revolutionise the era of intelligent and self-configurable objects. IoT refers to “a worldwide network of interconnected objects uniquely addressable, based on standard communication protocols” [3]. Because of the former mentioned developments, the amount of data is increasing unabated. The increased amount of data is particularly of interest for the technologies such as the Cloud computing as well as big data analytics. It becomes, therefore, important to understand these characteristics and challenges as well as the positive aspects that these developments might bring into the organisations.

The current paper goes through several important aspects of the digitalisation efforts to achieve Industry 4.0 in the industrial domain, especially in industrial maintenance. Consequently, the paper goes through the CBM approach as well as emergent technologies that have the potential to revolutionise maintenance and move it into Industry 4.0.

Continuously, in section 2, the CBM approach is examined and discussed, followed by developments in the MEMS sensors that merge micromechanical and microelectronic in Section 3. In section 4, the IoT advances and characteristics are illustrated. Section 5 highlights the big data analytics, which becomes crucial with the recent developments. Section 6 will describe Cloud computing and the relationship between sensor technology and IoT systems. Thereafter, the discussion and conclusions are presented.

II. CONDITION BASED MAINTENANCE

CBM is a predictive maintenance strategy that is increasing in popularity due to the necessity of keeping the Overall Equipment Efficiency (OEE) as high as possible. Downtime reduction consists of the reduction of unplanned shutdowns and better utilisation of the necessary, planned and unavoidable downtimes through better scheduling and planning. Better scheduling and planning is made possible by the knowledge and time gained through condition monitoring and predictive strategies.

According to the Machinery Information Management Open System Alliance Open System Architecture for Condition Based Maintenance (MIMOSA OSA-CBM), a full CBM system is composed of various modules. The six functional blocks that conform a CBM system are the Data Acquisition (DA), Data Manipulation (DM), State Detection (SD), Health Assessment (HA), Prognostics Assessment (PA) and Advisory Generation (AG) (www.mimosa.org).

The data acquisition phase consists of various elements. A transducer or sensor is used to convert physical phenomena into an electrical signal. This signal is "filtered" to reduce or remove unnecessary noise before it is sent to the processing phase. Many times, amplification is also needed in the signal chain. If the output of the sensor is an analogue signal, it must be converted to a digital signal through an analog-to-digital (ADC) converter.

Once the signal is clean, it is sent to the processing element, usually a computer. In the Data Manipulation phase, different algorithms are applied to obtain meaningful information. Some examples of these algorithms are kurtosis, Fast Fourier Transform (FFT) and envelope analysis. The outcomes of the algorithms are stored in a database as a historical data and, depending on the application and the number of samples, sometimes the raw data are also stored in databases.

In the State Detection phase, some "baselines" are created, and the newly gathered information is compared to historical data to analyse if there are any abnormalities, and, if so, in which profile the abnormalities belong.

The main objectives of a CBM system are the Health and Prognostic Assessment blocks. With the meaningful information obtained from the various algorithms, a diagnosis is carried out to analyse the asset's current health level. Once the diagnosis is completed, a prognostic is made to predict the performance and the Remaining Useful Life (RUL) of the asset in the future.

Finally, the outcome of the prognostic block is used to take the necessary maintenance actions to optimise the life cycle of the component or asset. The Advisory Generation (AG) is usually linked to the Computerized Maintenance Management System so that the recommended actions could be automated. As an example, if the AG block determines that a component's RUL is two months, it should find the best moment to schedule maintenance so that the downtime of the element is as low as possible.

III. MEMS SENSORS MERGE MICROMECHANICAL AND MICROELECTRONIC

Micro-Electro-Mechanical Systems (MEMS), also known as Micro-Systems Technology (MST) and Micro-machining are miniaturised mechanical and electromechanical elements that are made using the techniques of micro-fabrication [4]. The size of these systems may vary from as small as 1 micron up to a few millimetres. Functionally, a MEMS will typically have four components; micro-structures, micro-electronics, micro-sensors and micro-actuators. Micro-electronics is the brain of the system that gets inputs from the micro-sensors which act as the sensory organ for the system. Micro-sensors measure mechanical, thermal, biological, chemical, optical, and magnetic phenomena and pass this information to the brain of the system i.e., the micro-electronics.

Based on the inputs, micro-electronics commands the micro-actuators to perform some tasks. The micro-actuators respond by moving, positioning, regulating, pumping, and filtering, thereby controlling the environment for some desired outcome or purpose. The integration of the sensor with some processing capabilities in the same integrated circuit also enables the lowering of the price while maintaining a small size. Another advantage of the MEMS sensors is the ability to easily integrate them into systems without altering or having to modify it greatly. The low power consumption of these sensors also makes them appropriate for CBM systems.

MEMS are usually built using modified versions of semiconductor device fabrication technologies such as moulding and plating, wet etching or dry etching among others [5]. The way these MEMS are fabricated enable them to be relatively low priced compared to the classical sensors.

Both micro-transducers and micro-actuators are the transducers that transform one form of energy to other. Micro-sensor is a device that typically converts a measured mechanical signal into an electrical signal [6]. Micro-actuators, on the other hand, convert the electrical signal provided by the micro-electronics to mechanical movement of parts. These micro-actuators can perform a variety of tasks; micro-valves for control of gas and liquid flows; optical switches and mirrors to redirect or modulate light beams; independently controlled micro-mirror arrays for displays, micro-resonators for a number of different applications, micro-pumps to develop positive fluid pressures, micro-flaps to modulate airstreams on aerofoils, as well as many others (www.mems-exchange.org).

A MEMS-based accelerometer contains a polysilicon surface micro-machined sensor and signal conditioning circuitry to implement open-loop acceleration measurement architecture. This accelerometer outputs analogue voltages that are proportional to acceleration by sensing changes. The sensor converts the capacitance changes due to acceleration into a voltage [7]. These systems have found several usages in machinery fault diagnosis [8].

IV. INTERNET OF THINGS (IOT)

The term IoT was used to speak of identifiable interoperable connected objects with that contained radio-frequency identification (RFID) technology [9]. With time researchers started to relate IoT in conjunction with other technologies as well such as sensors, actuators, GPS devices, and mobile devices, etc. In recent years, several industrial IoT applications have been developed [10]. However, the IoT are still considered being in the nascent stages [11]. The authors mention that the IoT has provided companies with the possibilities to develop powerful industrial applications by means of leveraging the increase ubiquitous radio-frequency identification (RFID), wireless mobile as well as sensor devices.

The SOA architecture is a technology that has been successfully implemented in the area of cloud computing, and it is believed that it will have a positive impact on the IoT. A four-layer architecture is supposed to provide a holistic picture of the functionalities of an IoT architecture [10]. Thus, the first layer is a sensing layer where all the sensors are activated, i.e. sensing the physical world and acquiring data. The second named the Network layer gives a basic network support as well as data transfers by the support of Internet protocols. The third layer called Service layer generates and manages the various services provided to the different users. The last layer, i.e. the user interface layer provides possibilities for the user to interact with the IoT system.

The data sensing and acquisition means have become smaller and cheaper. The penetration of small unobtrusive sensors in our lives has made it easier to sense and acquire the data. The future data collection is going to become even bigger with IoT becoming a reality. The very idea that the objects around us will have sensors that can communicate with other objects points at the huge increase in data generated and collected. These objects will be able to measure, infer, understand, and even modify the environment [12].

Various industries could benefit in different ways from implementing the IoT. For example, the connectivity the IoT offers could be used remotely to update firmware, settings or follow the performance of a machine without having to be on location [13].

Another aspect where IoT could become beneficial is to upgrade or improve old equipment. The aforementioned new technologies such as MEMS or single-board computers are enabling to upgrade the old equipment and add features that could be used to do condition monitoring. This way, by externally adding the different sensors to the already available equipment, it will not be necessary to buy modern and expensive equipment, at least for condition monitoring purposes.

In 2011, Reliawind made a report that later Moog and DNV GL Research validated, it was identified the pitch system as the number one component that contributes to downtime and failure in wind turbines [13]. The researches realised that the batteries from the pitch system could be a reason why this systems were failing often due to the rough conditions: temperature, vibrations, humidity, etc. Consequently, they installed some sensors in the pitch system batteries with a communication protocol that enabled doing real-time monitoring of the batteries but also the pitch system. This way, they could also send automated email alerts if any of the components were being deteriorated. This system also provided a faster response for a diagnosis when there are any problems and automated ordering of replacement parts if needed. In this case, and others where the location of the equipment is difficult to reach, usually working parts are also repaired to take advantage of the trip. However, with condition monitoring, it might not be necessary to do so, and repair only the damaged parts.

IoT technologies will allow companies to collect and analyse large amounts of data in real-time, any potential problems are immediately identified allowing maintenance to undertake repairs. Detailed data collection and analyses will provide an accurate history of current failures/issues, and more importantly potential failures, therefore, allowing the company to introduce CBM systems on components and sub-components which had not been identified as potential problems previously due to inaccurate data or in appropriate maintenance tasks.

V. BIG DATA ANALYTICS

Big data is defined by its characteristics, i.e. the 3 V's, i.e. volume, variety and velocity [14]. The volume is connected to the increased amount of data that is produced, such as, transactional-based data, text data from social networks, and increased amount of sensor data being collected etc. The variety has to do with the different formats of data that is generated and stored like sensor data, video, audio, xml etc. The velocity is connected to how fast the data is produced as well as how fast the data needs to be processed, i.e. gathered, stored, and analysed.

The developments mentioned in previous sections such as the developments in sensors and IoT results in large amount of data being created. The data streams coming from these devices will start to move companies into emerging paradigm of big data [15]. These developments require that organisations affected by these changes to invest in big data technologies to be able to make use of the data and information and by doing so provide value to the company. It means that the sensors and IoT are producing a large amount of data, often called big data. Industry has been using the data and its analysis in order to arrive at decisions for a long time now. In the field of asset management too, decision making has been supported by the introduction of data analytics.

The methodology of data analysis for asset management has changed completely with the emergence of Big Data. The paradigm shift has come because of the characteristics of the Big Data. The data can now be more inaccurate due to the increase in volumes. High dimensionality of the data also means that it can be used to develop effective methods that can accurately predict the future observations and at the same time to gain insight into the relationship between the features and response for scientific purposes. In addition, large sample size helps with; firstly, exploring the hidden structures of each subpopulation of the data, which is traditionally not feasible and might even be treated as ‘outliers’ when the sample size is small; and secondly, extracting important common features across many subpopulations even when there are large individual variations [16].

The data being collected has a wide variety; from being digital (temperature of machines, oil consumption, etc.) to analogue (videos, audio, employee complaints, customer reviews, etc.). The rising capability of “data fusion” makes it more and more possible to bring together disparate sources of data to glean fresh insights that nobody predicted [17]. Data-centric or big data engineering, recognizing the value of data as an asset in itself and places data considerations at the core of engineering design. It improves performance, safety, reliability and efficiency of assets, infrastructures and complex machines. Big Data has transformed from being “the next big thing in innovation” and the “new paradigm of knowledge assets” to a reality of our time [18].

VI. Cloud Computing

Improved methods to analyse the large volumes and varieties has made it worthwhile to collect and store this data. This improvement has happened at two levels. Firstly, there has been an improvement in the relevant areas of mathematics. Considerable progress has been made in representing massive data sets as networks of geometrical nodes and edges so that the data can be rationalized using a suite of mathematical tools known as topological data analysis (TDA) [19]. These new methods help in getting information out of a large amount of unstructured data. Secondly, there are suitable software platforms like MapReduce and Hadoop that make the handling of this complex data possible. These platforms divide the datasets to small pieces and then re-integrate them back after the analysis has been done. This division of data sets to smaller manageable pieces allows the computing resources to manage the data effectively.

Increased volume of data requires larger storage and computational resources. Companies today are generating, gathering and storing larger amounts of data. However, the companies are not able to install computational resources for data analysis that can complement this data deluge. It is becoming increasingly economically unviable for the companies to build in-house data analytic facilities. This has led to the development of cloud computing where the resources like networks, applications and servers can be hired for use. Organisations now have higher computing power available to them without having to establish and maintain such cost prohibitive infrastructure in their own premises [20]. Industries are moving towards the Cloud due to the efficiency of services provided by the pay-per-use pattern based on the resources such as processing power used, transactions carried out, bandwidth consumed, data transferred, or storage space occupied [21]. The service providers are better equipped to handle the business risks that get shifted towards them.

VII. Discussion and Conclusions

The path to both digitalisation and Industry 4.0 in the maintenance department has been made possible owing to the emergent ICTs. It is important, however, to base those developments on pillars such as the CBM strategy to have a common view of what the technologies should solve in the specific domain. In this paper, the authors have made efforts to highlight these aspects, i.e. the CBM approach as well as technologies such as sensors as well as related technologies such as the IoT, big data analytics and cloud computing. These developments move the area of maintenance into a new era where all these technologies enable the digitalisation and the successful implementation of Industry 4.0 in maintenance. The development of Industry 4.0 is a complex process where it is important to understand several aspects both at the conceptual level as well as by taking into account the characteristics of the emergent technologies to be able to use them in an optimal manner. Consequently, the digitalisation and Industry 4.0 provide new technologies as well as challenges for the maintenance department.

It is, therefore, necessary to understand the inter-connectivity between the aspects that have been described in this paper. The future of machine maintenance can be described as “MEMS based IoT system with Big Data Analytics that uses Cloud resources for the CBM of machines”. MEMS, with the ever-reducing costs and increasing processing powers, will find way to each of the machine that is being used. These sensors will pick up the data from the machines. As the number of sensors on the machines increases, the machines will start interacting with each other; thereby resulting in an IoT. The large number of sensors on the machines as well as a gigantic increase in their inter-communication will produce even larger amount of data. This large volume, variety and velocity of Big Data will render the normal computational resources as obsolete. There will be a requirement of higher power computational machines, which will be shared by the Cloud. The services of the cloud are available on pay-per-use basis, which will enhance the speed and depth of big data analytics being done to the large amount of data generated by the sensors. All this will make it possible to monitor the health of the machines in real time, without actually being present at the plant location. It is important to note that a system comprising IoT, Cloud, MEMS and Big data analytics will contribute to achieving Industry 4.0 targets. The four principles of Industry 4.0 that can be met by the combination of these technologies are as follows:

(a) Interoperability: The machines are able to talk to each other through the MEMS and IoT;

(b) Information Transparency: Aggregation of sensor data and its analysis will ensure that the health of the machines is monitored continuously and the information is available at all levels;

(c) Technical assistance: The cyber-physical system will provide assistance at two levels. Firstly, it will be able to collect, analyse and present data to the humans for better monitoring of the health of the machines. Secondly, it will assist the humans in carrying out tedious, unsafe and monotonous tasks;

(d) Decentralized Decisions: The system of sensors in the IoT will be able to take autonomous decisions. These decisions will be based on pre-fed logic that will help in reduction of delays, which is a result of the longer decision making process by humans.

However, the development of Industry 4.0 with all its networking has been made possible with the support of the Cyber physical systems, IoT, cloud-based big data for organisations and industries, etc., and is challenged by cyber security issues [22; 23; 24]. It is, therefore, important to understand various aspects that need to be considered to secure the data and information in an organisation, specifically when emerging technologies part of Industry 4.0 are used. Cyber security is crucial and it will become even more evident because of the developments of, for instance, sensors, IoT, and SOA such as the cloud computing approach. In addition, malicious hackers can get greater access to both the wireless communications and such physical devices as sensors. Reliability of the complete system of sensors and cloud resources gains greater importance when critical assets are considered. Moreover, the heterogeneity of a large number of sensors as well as the clouds can give rise to the problems of interoperability. The amount of data generation and collection will increase many folds. Data Management solutions will have to become more efficient and effective to deal with the data that will continue to grow.

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